The Potential of Air-Water Heat Pumps in a Belgian Residential Retrofit Context in relation to Future Electricity Prices

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1. ABSTRACT

Retrofitting plays an important role in reducing space heating energy demand in the Belgian residential building stock. Moreover, retrofitted buildings allow the application of low temperature heat emission systems combined with heat pumps. In this context, the potential of air-water heat pumps is assessed from an energetic and economic point of view, by considering multiple combinations of building retrofit options, heating system components and energy prices, resulting in different scenarios. Each scenario leads to a different space heating demand while domestic hot water demand is equal in all cases. Results of dynamic simulations in Modelica show that retrofitting the building envelope is always beneficial from an energetic point of view, but the economic viability strongly depends on the age of the dwelling and energy prices. Regarding the heating system, a single stage heat pump combined with a low temperature heat emission system, amongst which the recuperated original radiators are also taken into account, leads to the lowest energy use. A gas condensing boiler is still the most cost effective solution with current prices in Belgium, but the ratio between mean electricity price and gas price appears to be one of the most important drivers for the competitiveness of heat pumps.

Keywords: Air water heat pump, hybrid heat pump, fan supported radiator, retrofit, residential, electricity price profiles

Nomenclature

CAPEX	Capital expenditures
DHW	Domestic hot water
DPP	Dynamic pay back period
FH	Floor heating
FSR	Fan supported radiators
GCB	Gas condensing boiler
HDD	Heating degree days
HTHP	High temperature heat pump
LTHP	Low temperture heat pump
NZEB	Nearly zero energy building
OPEX	Operational expenditures
PPD	Predicted percentage of dissatisfied
TCO	Total cost of ownership

The work of Evelyn Heylen is funded by the Research Foundation - Flanders (FWO)
KU Leuven is founding member of EnergyVille

2. Introduction

Climate change, large energy expenses and energy security have made the European Union set strict regulations within energy policy, amongst which regulations considering the electricity sector and residential buildings. The former regulations are expected to lower the CO_2-intensity of electricity generation in the future (Delarue et al., 2011; Keay, Rhys, & Robinson, 2012). The latter regulation is the European Energy Performance of Buildings Directive (EPBD) and regulates the energy performance of new dwellings (The European parliament & the Council of the European Union, 2010). However, presently the existing residential building stock accounts for 25% of total energy use in Europe (Poel, van Cruchten, & Balaras, 2007), of which 82% for domestic hot water (DHW) production and space conditioning (Pérez-Lombard, Ortiz, & Pout, 2008). Therefore, the existing building stock presents a large potential for reducing energy demand, since in Europe more than 50% of today's buildings is built before 1970 and about 33% of the dwellings between 1970 and 1990 (Poel et al., 2007; Norris & Shielsn, 2004). Retrofitting older buildings can significantly lower energy demand, because it reduces the need for space conditioning (Verbeeck & Hens, 2005) and makes these buildings suitable for low temperature emission systems (Schmidt, 2009). The possibility of applying these emission systems, combined with the expected lower CO_2-intensity of electricity, can make heat pumps a competitive heating system as opposed to conventional heating solutions using fossil fuels. Especially air-source heat pumps are seen as an attractive option for residences, due to their lower investment cost compared to ground-coupled heat pumps (Cabrol & Rowley, 2012). The latter have benefits when the building has both heating and cooling loads, typically in the tertiary sector.

This paper investigates two approaches for decreasing the energy demand of old buildings. On the one hand, an improvement of the building envelope by insulating roofs, floor and walls and placing windows with high performance glazing is considered. Three generations of building stock, from the periods 1946 - 1970, 1971 - 1990 and 1991 - 2005, are retrofitted to the newest standards (Flemish Energy Agency (VEA), 2013). On the other hand, the reference gas condensing boiler (GCB) is compared to more energy efficient heating systems, being low and high temperature heat pumps (resp. LTHP and HTHP) and hybrid heat pumps (HHP). These heat production systems are combined with three heat emission systems, namely the recuperated radiators, fan supported radiators (FSR) and floor heating (FH). Well chosen system configurations that combine the two energy demand reduction approaches, are compared by performing dynamic simulations. The advantage of this methodology is that the energy use can be determined more precisely, since effects such as lower part load efficiencies and losses due to intermittent heating are included in the simulation models. These dynamic simulations are based on a global system approach using IDEAS component models (De Coninck, Baetens, Saelens, Woyte, & Helsen, 2014; Baetens et al., 2012) in the modelling language Modelica using Dymola as interface.

Various studies investigate the performance of heat pumps, but these studies generally lack to consider retrofitting the building envelope or other emission systems (Cabrol & Rowley, 2012; Huchtemann & Müller, 2012; Kelly & Cockroft, 2011; Van der Veken, Hens, Peeters, Helsen, & D'haeseleer, 2006). Results of these studies strongly depend on the boundary conditions considered, such as the CO_2-intensity of the electricity generation park and the primary energy factors. However, they indicate that lower CO_2-emissions are already possible if air water heat pumps are applied, even with current fuel mixes for electricity production (Huchtemann & Müller, 2012) .

Verbeeck et al. (Verbeeck & Hens, 2005) proposed a logical hierarchy of energy-saving measures, preferring insulation improvement of building components above more energy efficient heating systems and renewable energy systems. These conclusions were based on a static calculation procedure as stated in the Flemish Energy Performance Regulation (EPR) (Department of the Flemish community, 2006; Flemish government, 2006). This EPR calculation method will be used in the current work to verify results of dynamic simulations even though it does not contain the newest technologies such as hybrid heat pumps or fan supported radiators.

The aim of this work is to assess how various combinations of retrofit measures impact the energetic and economic potential of air-water heat pumps in a residential retrofit context. First, the assessment methodology is described in section 3, followed by an overview of data and models in section 4. The results of the energetic and economic analysis are summarized in section 5 and a discussion of the results is given in section 6. Finally, section 7 summarizes the main conclusions of the paper.

3. Methodology

The quantitative indicator in the energy analysis is primary energy use for heating cumulated over one year. The energy use considered in this study includes the gas use of the GCB ($P_{gas}(t)$ [W]), electricity needed for the electronics and the fan of the GCB ($P_{GCB,elec}(t)$ [W]) and the electricity use of the heat pump ($P_{HP}(t)$ [W]), circulation pumps ($P_{pumps}(t)$ [W]) and fan supported radiators ($P_{FSR}(t)$ [W]) if present. Mechanical ventilation and other electrical appliances are not taken into account. The conversion factor between electricity and primary energy is taken equal to 2.5 and 1 for natural gas to primary energy (Verbeeck & Hens, 2005). Equation (1) is used to calculate the primary energy use.

$$E_{prim} = \int_{1year} P_{elec}(t)dt \cdot 2.5 + \int_{1year} P_{gas}(t)dt \cdot 1 \tag{1}$$
$$\text{with } P_{elec}(t) = P_{HP}(t) + P_{pumps}(t) + P_{FSR}(t) + P_{GCB,elec}(t)$$

In order to make an honest energetic comparison, the indoor operative temperature needs to be within similar comfort bounds in every case (Peeters, de Dear, Hensen, & D' haeseleer, 2009; Van der Linden, Boerstra, Raue, Kurvers, & De Dear, 2006).

The economic viability of the retrofit options for the building envelope and the heating system is evaluated based on two indicators, namely the total cost of ownership (TCO) [€] and the dynamic pay back period (DPP) [years]. The total cost of ownership (Verbeeck & Hens, 2005; Kaynakli, 2012) is a financial indicator which is used to assess the viability of a certain investment by actualizing all associated costs over a period:

$$\begin{aligned} TCO =& I_0 + \sum_{x,y,z} \frac{I_j}{(1+a_g)^j} + \sum_{i=1}^{n} \left[\frac{K_{elec}(1+r_{elec})^i}{(1+a_g)^i} + \frac{K_{gas}(1+r_{gas})^i}{(1+a_g)^i} + \right. \\ & \left. \frac{K_M(1+r_M)^i}{(1+a_g)^i} + \frac{K_{CO_2}(1+r_{CO_2})^i}{(1+a_g)^i} \right] \end{aligned} \tag{2}$$

In this study, the costs of initial investment I_0 and reinvestment I_j in the years x,y and z, and the annual costs of maintenance K_M, electricity K_{elec}, gas K_{gas} and CO_2-emissions K_{CO_2} are considered to determine the TCO. Investment costs consist of material costs of different elements of the heating system and the improvement of the building envelope, labour cost and 6% VAT (Federal State Service for Finances, 2012). Prices of the installations used are a combination of prices and information of manufacturers complemented with prices of research centers as shown in table 1. Prices of retrofit measures of the building envelope are given in the lower part

Table 1: Investment costs of installations and prices of retrofit measures of the building envelope based on updated information from (De Coninck & Verbeeck, 2012) and manufacturers' data.

Installation	Price I_0 [€] [1]	Maintenance [€/year]	Life time [years]
GCB	2605	$0.02I_0$	20
HHP	6000	$0.04I_0$	20
LTHP [2]	$424.73 \cdot \dot{Q}_{nom,2/35} + 2996.8$	$0.04I_0$	20
HTHP [2]	$322.32 \cdot \dot{Q}_{nom,2/35} + 5645.7$	$0.04I_0$	20
FSR [3]	$1379 \cdot$ #pieces	///	>35
FH [3,4]	$740 \cdot \dot{Q}_{nom} + 109$	///	>35

[1] Excl. VAT
[2] $\dot{Q}_{nom,2/35}$ = Nominal power of the heat pump at 2°C/35°C [kW]
[3] Labour cost included
[4] $\dot{Q}_{nom}$ = Heat power demand of the building by prEN 12831 [kW]

Retrofit measure	Price I_0 [€] [1]
Roof insulation	$132 \cdot$ Volume insulating material [m^3]
Floor insulation	$221 \cdot$ Volume insulating material [m^3] + $4 \cdot$ Floor area [m^2]
Facade insulation [2]	$265 \cdot$ Volume insulating material [m^3] + $93 \cdot$ Facade area [m^2]
Facade insulation [3]	$22 \cdot$ Facade area [m^2]
Windows	$328.5 \cdot$ Window area [m^2]
Air tightness	$8.5 \cdot$ Surface area to the outside [m^2]

[1] Excl. VAT and labor cost included
[2] Outside insulation of the facade
[3] Cavity filling

of table 1 (based on updated information from (De Coninck & Verbeeck, 2012)). The heating system and the windows need reinvestments every 20 and 25 years respectively. Local subsidies are not taken into account.

Next to the capital expenditures (CAPEX), operational expenditures (OPEX) consist of maintenance costs, energy costs and CO_2-costs. Annual maintenance cost is expressed as a percentage of the investment cost (Parys, 2013), as indicated in table 1, and prices of gas and electricity are summarized in table 2. Only CO_2-emissions associated with energy use for heating in the dwelling are taken into account, thus embedded CO_2 is out of the scope of this research. As shown in the third and fourth column of the upper part of table 2, CO_2-cost is only a fraction of the total cost. As long as CO_2-costs do not rise significantly, these will not have a significant influence on the conclusions of the economic analysis.

Due to the variability of several cost parameters in the future, different scenarios are proposed. CO_2-prices and maintenance costs are kept constant in this study (r_M and r_{CO_2} equal 0). r_{gas} and r_{elec} represent the yearly percentage increase on top of the inflation of respectively the gas and electricity price, as shown in table 3. The exponent i in equation 2 corresponds to the considered year, while n is the period under consideration, which equals 50 years in this study. The actualisation rate a_g equals 2.5%.

The second evaluation method, the dynamic payback period, is defined as the period after which benefits outweigh costs. Contrary to the static payback period, the dynamic payback period

Table 2: The upper part summarizes energy prices (Flemish regulator of the electricity & gas markets (VREG), 20/05/2013; Eurostat European Commission, 2013) and CO_2-emissions (Verbeeck & Hens, 2005; Van der Veken et al., 2006) in the Belgian context. The last two columns show the total resource cost, CO_2-emissions included for two different CO_2-costs. The lower part gives the average, maximum and minimum value, and standard deviation of the variable electricity price profiles for France, Belgium and Germany.

Resource	Price [€/kWh]	CO_2-emissions [kg/kWh]	Price + CO_2-cost €4.5/ton [€/kWh]	Price + CO_2-cost €40/ton [€/kWh]
Gas	0.07	0.2	0.0709	0.0780
Electricity (night)	0.15	0.31	0.1514	0.1624
Electricity (day)	0.25	0.31	0.2514	0.2624
Variable Electricity price	**Average [€/kWh]**	**Maximum [€/kWh]**	**Minimum [€/kWh]**	**σ [€/kWh]**
France	0.14	0.27	-0.11	0.020
Belgium	0.22	0.35	-0.03	0.019
Germany	0.28	0.38	0.15	0.016

Table 3: Evolution of energy prices in Europe over the past 13 years. Yearly increases in terms of percentage are on top of the inflation (European commission, 2012; Flemish regulator of the electricity & gas markets (VREG), 20/05/2013)

Region or country	Yearly increase r_{gas} [%]	Yearly increase r_{elec} [%]
EU15	3.5	1.2
Germany	4.4	4.0
Belgium	4.0	1.6
Used yearly increase	4.0	2.1

takes into account derating of cash flows.

4. Case study and modelling

For this study, three representative dwellings constructed in different time periods are considered, each having construction components with an insulating quality that is typical for the respective building period in Belgium. As a reference case, all original dwellings are considered to be equipped with a gas condensing boiler and radiators designed for a supply temperature of 75°C and a temperature difference of 10°C.

4.1. Dwellings

The national brochure about the Belgian dwelling typology (Holm, Verbeke, & Stoppie, 2011) identifies different generations in Belgian building standards of which three generations are considered in this study, namely 1946-1970, 1971-1990 and 1991-2005. Table 4 summarizes typical parameters of the building envelope for each generation and values of these parameters after retrofitting the building in order to meet the requirements of EPB2014 energy regulations for buildings in Flanders (Flemish Energy Agency (VEA), 2013). The additional insulation of the facades is assumed to be added at the outside wall of the building. This technique requires higher investment costs than other insulation techniques, but the narrowness or absence of a cavity in walls of older building generations implies this insulation technique.

Table 4: Overview of building envelope parameters for considered building generations and after retrofitting (Retr) (Holm et al., 2011; Hens, 2010)

U-Value [W/m^{2}K]	'46-'70	'71-'90	'91-'05	Retr
Facade	1.7	1	0.6	0.24
Roof	1.9	0.85	0.6	0.24
Floor	0.85	0.85	0.7	0.3
Windows	5	3.5	3.5	1.8
Door	4	4	3.5	2
n_{50}-value [h^{-1}]	10	7	7	4
Heat power demand [kW]	29.3	18.2	14.5	8.7

In order to make reasonable comparisons for different generations, all dwellings are considered to be detached houses with the geometrical characteristics of the average Belgian detached dwelling as determined in the EL^{2}EP study (Verbeeck & Hens, 2002) based on statistical data. The geometry of the dwellings is given in appendix A. The protected volume is 565 m^3, the floor surface area 93 m^2 and the total external surface area 421 m^2. Table 5 summarizes percentage of glazing compared to the overall area of facades in different orientations.

Table 5: Areas of construction components complemented with the share of glazing in a particular building component

Building component	Area [m^2]	Percentage glazing [%]
Northern facade	47	1
Southern facade	58	19
Eastern facade	48	16
Western facade	48	14
Floor	93	-
Southern roof	54	-
Northern roof	73	-

The building is considered to be a single zone with convective and radiative heat transfer towards high order lumped capacitance building components (Baetens & Saelens, 2011). Building components such as facades, roofs and floors consist of typical Belgian construction layers. Facades as from generation 1971 - 1990 have typically an inner and outer wall with a cavity, eventually filled with insulation. The heat demand of every dwelling is calculated based on the EN12831-standard (European committee for standardization, 2003) using a design outside temperature of -10°C and an inside design temperature of 20°C for the single zone building.

4.2. Heating systems

Four heat production systems and three heat emission systems are considered. The considered heat production systems are: a gas condensing boiler (GCB), a low temperature heat pump (LTHP), a high temperature heat pump (HTHP) and a hybrid heat pump (HHP). The low temperature heat pump uses a single compression stage and can deliver heat up to a supply temperature of 60°C, while the high temperature heat pump employs two compression stages in order to reach supply temperatures of 80°C. These supply temperatures determine whether the system is considered in a certain scenario or not.

The models of the LTHP and gas condensing boiler are based on manufacturers' data and component models taken from the IDEAS library[3] (De Coninck et al., 2014; Baetens et al., 2012). In case of the heat pump, manufacturers' data give the thermal and electrical power as a function of the ambient air temperature, the supply temperature to the emission system and the frequency modulation of the heat pump compressor. For the GCB, the efficiency of the boiler is given as a function of mass flow rate and supply temperature to the emission system. The model of the HTHP is similar to the one of the LTHP, but based on other manufacturers' data. The LTHP and the HTHP, having a COP of 3.31 and 3.28 at 2°C/35°C respectively, are sized based on their heat power delivered at -10°C outside temperature and the required supply temperature of the emission system (-10°C/T_{supply}) at 100% modulation in order to deliver the heat power demand as shown in the last row of table 4.

The hybrid heat pump is a combination of a LTHP and a GCB and is able to switch between the two devices depending on which of the two is the most cost effective at a specific moment in time. The model of the hybrid heat pump combines the model of the GCB and the LTHP complemented with an algorithm that controls the switching between the two devices based on cost effectiveness (Heylen & Jordens, 2013).

The three heat emission systems considered in this study are radiators (Rad), floor heating (FH) and fan supported radiators (FSR). In all buildings before retrofit (denoted with 'O' in table 6) radiators are installed with a nominal supply and return temperature of 75°C and 65°C, respectively. After a retrofit (denoted with 'R' in table 6), it is possible to recuperate these radiators. This results in a lower required supply temperature, because the nominal power of the radiators is higher than the heat demand of the dwelling, which makes the installation of a heat pump more attractive (Radson, 2012).

Floor heating is only considered in the retrofitted building, since the floor needs to be sufficiently insulated in order to use this emission system and the supply temperature should be kept below an upper limit, which limits the available heating power. Floor heating is modelled as a thermal resistance and capacitance circuit that transfer heat of water in embedded pipes through the floor to the room.

Fan supported radiators have a higher heat transfer coefficient than conventional radiators due to the combination of forced (fan assisted) convection and radiation, which lowers the needed supply temperature. They can be used in four different fan states. The model of the fan supported radiator is an extension of the model of the conventional radiator (similar to equation 3) with a heat transfer coefficient depending on different states of the fan as given by equation 4. As the nominal power of the four states $\dot{Q}_{nom}$ differ, the model will change the heat transfer coefficient of the FSR depending on the state of the fan. For a conventional radiator, the heat transfer coefficient in equation 4 remains constant and is calculated using nominal values. The equations of the conventional radiator model are the same as equations 3 and 4, with all values

[3] https://github.com/open-ideas/IDEAS

replaced by the respective values of the conventional radiator and a fixed nominal power $\dot{Q}_{nom}$.

$$\dot{m}\Delta h + \dot{Q}_{total} = (m_{water}c_{p,water} + m_{drymass}c_{p,drymass})\frac{dT_{avg,FSR}}{dt} \tag{3}$$

$$\text{with } \dot{Q}_{total} = UA(0.5(T_{sup} + T_{ret}) - T_{zone})^{m}$$

$$\text{and } UA = \frac{\dot{Q}_{nom}}{(0.5(T_{sup,Nom} + T_{ret,Nom}) - T_{zoneNom})^{m}} \tag{4}$$

$\dot{m}$	Mass flow rate of water through the FSR [kg/s]
Δh	Enthalpy difference between inlet and outlet of the FSR [J/kg]
m_{water}	Mass of the water in the FSR [kg]
$m_{drymass}$	Dry mass of the FSR [kg]
$c_{p,water}$	Specific heat constant of water [J/kgK]
$c_{p,drymass}$	Specific heat constant of the material of the FSR [J/kgK]
$T_{avg,FSR}$	Average temperature of the FSR [K]
$\dot{Q}_{total}$	Emitted heat power of the FSR [W]
T_{sup}	Supply temperature [K]
T_{ret}	Return temperature [K]
T_{zone}	Temperature of the zone [K]
m	Exponent of emission (i.e. 1.1 for FSR and 1.3 for radiators based on manufacturers' data)
$\dot{Q}_{nom}$	Nominal power of the respective state of the FSR, constant value for conventional radiator

$T_{i,nom}$ is indicating the nominal values of the respective temperatures. The algorithm to control switching between the four states of the fan can be found in (Heylen & Jordens, 2013).

Sizing of the FSR is based on data from manufacturers that give the nominal power in the four fan states as a function of the temperature difference between room and mean temperature of the FSR. On the one hand, it is advisable to keep the supply temperature as low as possible to increase the efficiency of the heat production device. On the other hand, this increases the investment cost because more radiator units are needed due to lower heat emission per unit. The used FSRs have a nominal power emission of respectively 204 W, 796 W, 1084 W and 1452 W in the four fan states at a mean temperature difference of 20°C between radiator and zone. The needed number of units to supply sufficient heat is determined based on the maximal power emission of 1452 W and the heat demand of table 4.

Table 6 summarizes combinations of heat production systems and heat emission systems that are considered. Combinations are selected based upon the required supply temperature of the emission system, as given between brackets. After a retrofit of the building envelope of the older dwellings, the recuperated radiators can be supplied with water at a lower temperature, as they were originally sized for a larger heat demand. Domestic hot water (DHW) profiles are the same in all dwellings and they are supplied by the heat production system that generates the space heating demand.

4.3. Heating curve control

The set point temperature of the heat production system is controlled using a heating curve approach (De Coninck et al., 2010), which determines the supply temperature to the emission

Table 6: Overview of considered combinations of heat production systems and heat emission systems. (Rad = radiators with nominal power expressed at 75/65/20 °C)

	GCB	HHP	HTHP	LTHP
Rad 1946-1970	O(75) R(45)	R(45)	O(75)	R(45)
Rad 1971-1990	O(75) R(55)	R(55)	O(75) R(55)	R(55)
Rad 1991-2005	O(75) R(60)	R(60)	O(75) R(60)	
FSR		R(45)		O(45)R(45)
FH		R(35)		R(35)

O(x): Original state (without retrofit of building envelope)
R(x): Retrofitted state (with retrofit of building envelope)
x: Supply temperature [°C]

system as a function of the ambient temperature as given by equation 5.

$$T_{sup} = T_{zone} + \left(\frac{T_{sup,Nom} + T_{ret,Nom}}{2} - T_{ret} \right) [z_{rel}^{m}]^{-1} + \left(\frac{T_{sup,Nom} - T_{ret,Nom}}{2} - T_{ret} \right) z_{rel} \tag{5}$$

with $z_{rel} = \frac{T_{zone} - T_{amb}}{T_{zone} - T_{design}}$ [/], T_{zone} the actual room temperature [°C], T_{sup} the supply temperature [°C], $T_{sup,Nom}$ the nominal supply temperature [°C], T_{ret} the return temperature of the emission system, $T_{ret,Nom}$ the nominal return temperature, T_{amb} the ambient temperature [°C] and T_{design} the minimal ambient temperature used in the nominal heat demand calculation [°C]. The exponent m depends on the characteristics of the heat emission system and equals 1.3, 1.1 and 1 for radiators, FSR and FH respectively. (Hens, 2010; CEN, 2006)

4.4. Boundary conditions

Inhabitants are assumed to be present between 7 am and 10 pm, during which the set point of the room temperature is 20 °C. Outside this period, the set point is taken to be 16 °C. This study is carried out using Belgian climate data measured in Uccle (Brussels) (2002). In order to assess the influence of different electricity price profiles as given in table 2, the simulations are repeated for the climate data of 2013, a year for which whole sale market prices are available. The characteristics of both climates, i.e. average temperature T_{avg}, maximal temperature T_{max}, minimal temperature T_{min} and heating degree days (HDD) with respect to 16°C (Hens, 2010) are summarized in table 7.

Table 7: Overview of the climate characteristics of 2002 and 2013 of Uccle (Brussels).

Year	T_{avg} [°C]	T_{max} [°C]	T_{min} [°C]	HDD
2002	10.9	29.3	-7.5	2210
2013	10.2	35.2	-9.1	2364

5. Results

Figure 1 compares the total cost of ownership (TCO) before and after retrofitting the building envelope for various generations of dwellings. The bar graph differentiates the types of costs that are involved in a retrofit. Part of the CAPEX of the building envelope, namely €29420, is equal in the three cases, due to the costs of new windows, air tightness improvement and the large share of labour cost that are equal for all generations irrespective of the level of improvements. Next to that, the variable part of the CAPEX of the building envelope and investment costs of installations have to be added and finally operational costs, namely energy costs, CO_2-costs and maintenance costs.

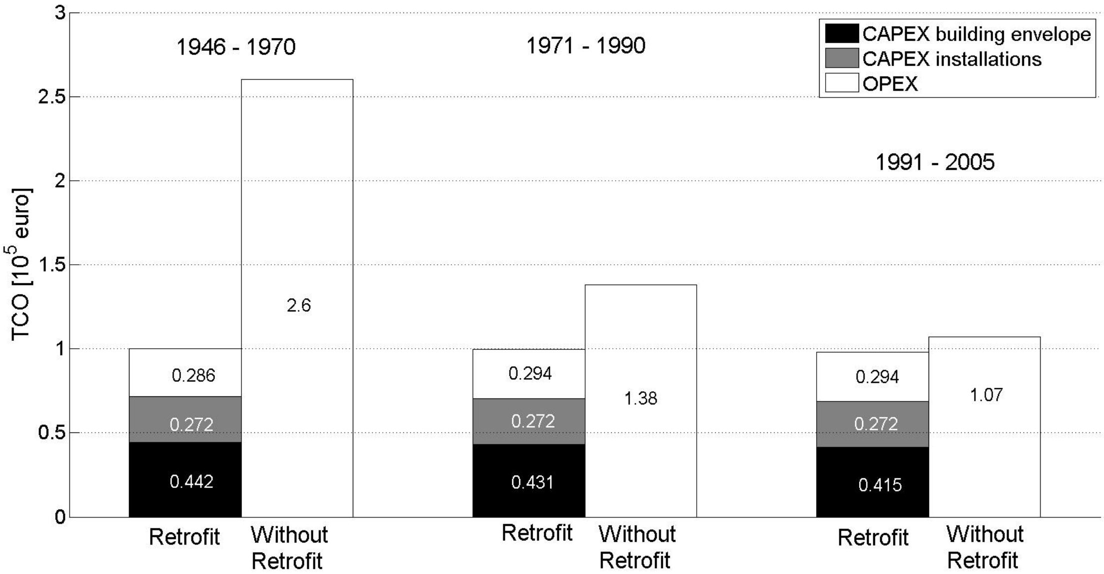

Figure 1: Average total cost of ownership for a period of 50 years of the three considered building generations for relevant combinations of the heat emission and production system as stated in table 6, with and without a retrofit of the building envelope. Energy prices rise according to scenario 1 (r_{gas} = 4% and r_{elec} = 2.1%).

Benefits of a building envelope retrofit in the oldest generation are clear as shown by the large difference in TCO with and without retrofit in figure 1, but in more recent generations, profits strongly depend on the evolution of energy prices. Also table 8 clarifies this, as the DPP is much higher when energy prices remain constant.

Table 8: Summary of average dynamic pay back periods (DPP) for retrofitting the building envelope of dwellings of different generations for relevant combinations of the heat emission and production system as stated in table 6. Comparison between outside insulation of the facade and filling of the cavity wall. Standard deviation for different combinations of heat emission and production system is given between brackets

Outside insulation DPP [years]	1946 - 1970	1971 - 1990	1991 - 2005
Rising energy prices	14.3 (0.9)	31.3 (1.9)	47.5 (3.1)
Constant energy prices	24.2 (5.2)	> 50	> 50
Filling cavity wall DPP [years]	**1946 - 1970**	**1971 - 1990**	**1991 - 2005**
Rising energy prices	-	19.9 (3.6)	41.1 (3.3)
Constant energy prices	-	32.3 (7.6)	> 50

Expensive outside insulation of the facade leads to these limited benefits in more recent dwellings. From a pure economical point of view, outside insulation can even not be cost effective in recent dwellings. However, this insulation technique incorporates an aesthetic advantage by completely renewing the facade of dwellings. When cavity filling is used in the two most recent generations, the DPP reduces considerably, as shown in table 8. If it is possible to apply the latter insulation technique, it is preferred over outside insulation of the facade.

Table 9 compares the different emission systems for the retrofitted dwelling. This table shows the average relative TCO of appropriate combinations of heat production and emission systems as indicated in table 6 for a retrofit of the three original dwellings of different ages. The TCO of different solutions is expressed relatively to the TCO of the solution with maximal TCO, in this case fan supported radiators. Radiators or a new floor heating system have nearly the same TCO after retrofitting the building envelope and are nearly 10% cheaper over a 50 year period than FSR. From the energetic point of view, however, the FSR has the highest potential of reducing the primary energy demand of the dwelling, as shown in the last column of table 9, which shows the relative primary energy demand. Radiators have the advantage that no extra labour is needed, but the floor heating system and FSR require a lower supply temperature, which leads to a higher efficiency of the heat production system counteracted by the higher investment cost. The relative cost effectiveness of the emission systems is nearly independent of the evolution of the energy (natural gas and electricity) prices.

Table 9: Comparison between different emission systems after retrofitting the building envelope. The second column presents TCO expressed relatively to the TCO of the device with maximum TCO. The third column shows the standard deviation for combinations with various production systems as stated in table 6, while the fourth and fifth column indicate the relative average primary energy use with respect to the FSR and the standard deviation, respectively.

Emission System	Relative TCO [%]	σ_{TCO} [%]	E_{prim} [%]	$\sigma_{E_{prim}}$ [%]
Recuperated Radiator	90.1	6.5	107.4	11.7
FH	92.3	6.8	101.9	11.9
FSR	100	4	100	10.5

Without a retrofit of the building envelope, heat emission systems' performance strongly depends on the efficiency of the heat production device. In the oldest dwelling, a lot of energy can be saved by using fan supported radiators in combination with a low temperature heat pump. This results in a lower total cost of ownership than using radiators. However, the energy saved by retrofitting the building envelope is much higher, so ignoring a retrofit of the building envelope is not advisable. In newer generations of dwellings, the absolute reduction of energy is more limited and radiators are a more economically favorable solution.

Using the recuperated radiators is not the best option from an energetic point of view, however the results are not far behind FH and FSR. Thus, from an economical point of view, using the existing radiators can be profitable. Therefore, figure 2 shows the comparison of the different heat production systems with (recuperated) radiators as emission system for the retrofitted building envelope. Thermal discomfort is expressed using hot degree hours and cold degree hours, which are defined as the temperature difference respectively above and below the temperature limit of a predicted percentage of 10 % of dissatisfied (PPD) multiplied by the duration of the limit violation. The level of discomfort is of the same order of magnitude for different heating system configurations, which allows a correct comparison of different system configurations based on annual primary energy use.

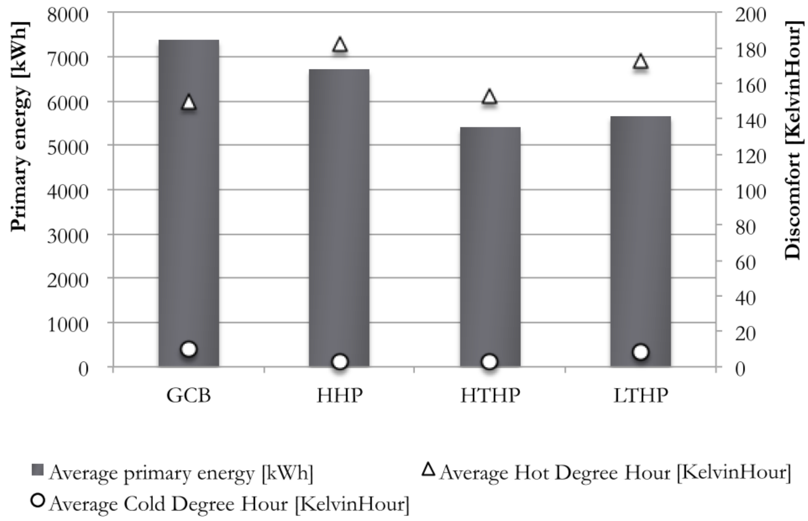

Figure 2: Annual primary energy use of heat production systems combined with radiators in a retrofitted building envelope with the current (2013) Belgian energy prices used for all production systems.

The lowest primary energy demand with radiators as emission system is obtained with a HTHP. The results of the LTHP are almost similar, although if an emission system is used that requires a lower supply temperature, the primary energy use of a LTHP reduces significantly. Therefore, a HTHP especially makes sense when relatively high supply temperatures are required, e.g. radiators in older buildings. Since the HHP combines a GCB and a LTHP, one expects its energy use to be between this of a GCB and a LTHP. The simulations show that the HHP behaves mainly as a LTHP when the gas price is relatively high compared to the electricity price and vice versa. The economic viability of the hybrid heat pump strongly depends on the energy cost savings that can be made with respect to the GCB by choosing for the most cost effective device, i.e. LTHP or GCB. Therefore, the ranking of heat production devices in combination with radiators based on TCO is influenced by the age of the dwelling. The age of the dwelling determines the supply temperature when the original radiators are recovered after retrofitting the building envelope and thus the efficiency of the heat production system, which determines possible energy savings. Table 10 compares the TCO of different heat production systems that supply heat to radiators with a retrofitted building envelope. If energy prices are constant (scenario 2), the gas condensing boiler outperforms the others, but an increase of energy prices (scenario 1) nearly levels out the differences. In the oldest generation, TCO of the hybrid heat pump is even smaller than TCO of the GCB for two reasons. First, the low temperature heat pump in the hybrid heat pump is used more in this case, because it can use a working point with a higher efficiency due to the lower supply temperature of recovered radiators. Secondly, the rapid increase of the gas price favors the use of electricity. However, in more recent dwellings higher investment costs of the hybrid heat pump with respect to the gas condensing boiler cannot be recovered, because the nominal power of the recovered radiators is lower than in the older buildings, so required supply temperatures are higher. Therefore, the hybrid heat pump uses working points with lower efficiencies, thus its gas condensing boiler will be preferred over its low temperature heat pump. As a consequence, there will be no net benefit compared to the gas condensing boiler. The high temperature heat pump is the most expensive solution.

The lower part of table 10 shows results with decreasing investment costs due to learning aspects in development and manufacturing of systems. A decrease of 1.6% per year is considered for all devices (Weiss, Junginger, & Patel, 2008; Weiss, Dittmar, Junginger, Patel, & Blok, 2009; Bettgenhäuser et al., 2013). This also lowers maintenance costs which are expressed as a percentage of investment costs. Due to these learning aspects, the cost effectiveness of the heat pumps improves. However, the GCB is still the most profitable solution, except for the oldest generation of dwellings with rising energy prices. Without learning aspects, the LTHP was approximately 5% more expensive in the generation 1971 - 1990 with rising energy prices than the GCB. With learning aspects included, the cost effectiveness of the LTHP comes close to that of the GCB. The relative cost difference between the GCB and the heat pumps reduces, because the GCB already walked through a large part of the learning curve. Therefore, reductions in investment cost are lower. Values for the HHP with learning aspects included are not given in table 10, because the learning curve is difficult to estimate for this novel device, which is the combination of two devices that walked through different parts of their learning curves.

Table 10: Comparison between TCO of heat production systems combined with radiators in buildings of three different ages after retrofitting the building envelope. The TCO is relatively scaled to the TCO of the gas condensing boiler. Scen 1 represents the first scenario with increasing energy prices. Energy prices are constant in scen 2. The upper part of the table does not take into account learning effects in investment and maintenance costs in contrast to the lower part.

Generation	LTHP		HTHP		GCB		HHP	
W/O Learning	Scen 1	Scen 2	Scen 1	Scen 2	Scen 1	Scen 2	Scen 1	Scen 2
1946 - 1970	104	125	110	133	**100**	**100**	97	113
1971 - 1990	106	127	110	133	**100**	**100**	102	115
1991 - 2005	110	131	116	140	**100**	**100**	106	119
W Learning	Scen 1	Scen 2	Scen 1	Scen 2	Scen 1	Scen 2	Scen 1	Scen 2
1946 - 1970	99	119	105	128	**100**	**100**	-	-
1971 - 1990	101	121	105	127	**100**	**100**	-	-
1991 - 2005	105	125	111	134	**100**	**100**	-	-

As the high temperature heat pump seems less economically interesting based on table 10, the focus will be on the LTHP, HHP and GCB. In order to assess the impact of the source of electricity generation in different countries on the potential of heat pumps, variable customer electricity prices can be considered as smart metering systems might become more wide-spread in the future. In this study, these prices are based on whole sale price profiles of 2013 (Epexspot, 2013) supplemented with grid tariffs, taxes etc. These supplements can be calculated by assuming the average of the variable price profile equal to the average price of the fixed price contracts in the different countries. The main characteristics of the variable electricity prices are summarized in the lower part of table 2. The simulations of dwellings with retrofitted building envelope and an heating system using radiators as emission system are repeated for different ratios of the average electricity price to average gas price, which results in figure 3. The climate data of 2013, as given in table 7, are used for these simulations. Figure 3 allows assessing the potential of a heat pump, if the ratio between the average electricity price and average gas price and the yearly energy cost for a system with GCB are known. It gives the yearly energy cost of a LTHP or HHP solution expressed relatively to the yearly energy cost with a GCB for different electricity price profiles. The maximum investment cost that can be paid back by the energy cost savings within the lifetime of the devices can be determined based on figure 3, if a certain evolution of the electricity prices and gas prices is assumed. The obtained investment cost can be compared with the current investment cost of the different types of heat pumps. The hybrid heat pump, which could effectively handle the price variations, is an effective investment in France, even if the current electricity and gas prices remain constant over the years. This is the case due to the much lower electricity costs as clearly shown in figure 3. In Germany, the electricity prices are much higher, which causes the gas condensing boiler to outperform the heat pump solutions. The results are mainly influenced by the average electricity price rather than by the price profile.

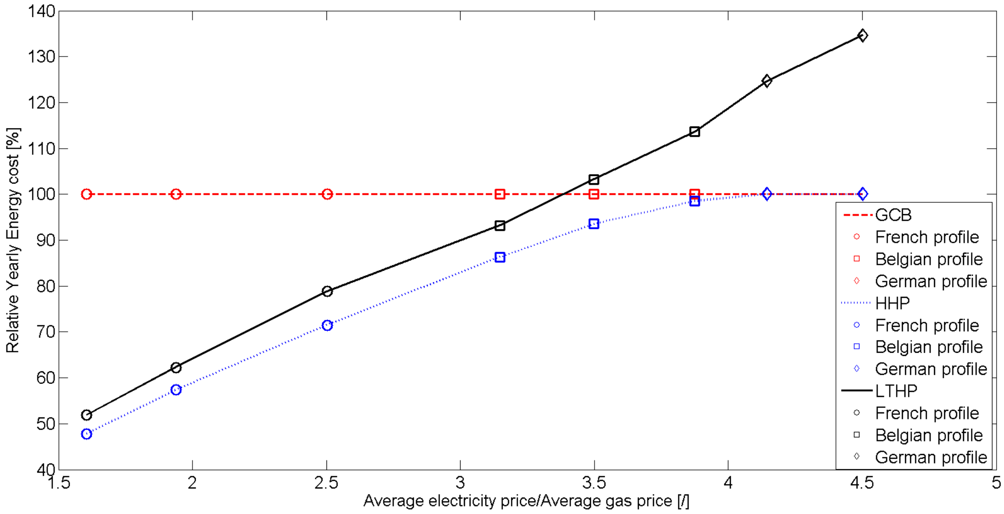

Figure 3: Yearly energy cost of the HHP and LTHP as a percentage of yearly energy cost of the GCB, as a function of the ratio of the average electricity price to the average gas price using electricity price profiles of France, Belgium and Germany after retrofitting the building envelope using radiators as heat emission system. The seasonal performance factor (SPF) of the LTHP equals 3.42. Results for the HTHP are very similar to the LTHP, and hence not shown.

6. Discussion of the results

The results show a large potential to cut costs and energy usage by retrofitting the oldest buildings. In order to lower primary energy use, a LTHP combined with FSR leads to the best result for both the retrofitted and non-retrofitted dwellings considered in this study. When the building envelope has been retrofitted, FH supplied by a LTHP is a very good alternative to FSR from an energetic point of view. Also using the existing radiators with the correct heat production system is possible, i.e. a LTHP with low supply temperature emissions systems and a HTHP when a higher supply temperature is required.

A comparison of the results with other studies is difficult due to the assumptions made. Nevertheless, table 11 compares the primary energy demand with the values of the Tabula project (Holm et al., 2011) for a Belgian single family house. The lower primary energy use averaged over the different heating systems for each generation compared to the Tabula study is amongst others the result of the retrofitting applied in this study. The heat production systems used in the Tabula project are a local stove with fuel oil (η = 75%) in generation 1946 - 1970, central heating with a fuel oil boiler (η = 70%) in generation 1971 - 1990 and central heating with a gas boiler (η = 76%) in generation 1991 - 2005, while this study also uses more efficient heat production systems such as heat pumps in the original dwellings. Therefore, the average primary energy use is lower. Next to that, the global heat insulation quality is worse in Tabula than in this study for generation 1946 - 1970 and 1971 - 1990 due to differences in the geometry and air tightness of the building. Another important aspect is the large amount of solar gains due to the large percentage of glazing in the southern facade of the considered dwelling. Finally, the static calculation method for the energy use applied in Tabula results in an overestimation of energy demand.

Table 11: Comparison of the primary energy use (E_{prim}) in the original dwellings averaged over various heating system in this study with values in the Tabula brochure (Holm et al., 2011).

Generation	Floor Area Tabula [m^2]	E_{prim} Tabula [kWh/m^2]	E_{prim} [kWh/m^2]
1946-1970	200	275.1	242.0
1971-1990	203	188.4	123.3
1991-2005	219.6	155.7	79.6

From an economic point of view, the literature confirms that the outside insulation of the facade is not an economically optimal measure. Therefore, investment costs are higher and primary energy use is lower in this study compared to the results of Verbeeck et al. (Verbeeck & Hens, 2005). Verbeeck et al. also consider insulation measures, especially roof and floor insulation, and better performing glazing, before more efficient heating systems, even though the total net present value might be similar or even lower. On the one hand, insulation has a longer life span than the heating system and on the other hand, the building's thermal quality determines the design and dimensions of the heating system with a risk of not being adapted if insulation is placed after replacing the installation. However, the aim of this paper is not to find the optimal solution but to compare different heating systems.

An important factor in the cost effectiveness of air source heat pumps is the evolution of the energy prices. It seems that current Belgian electricity prices are too high compared to gas prices, thus the energetic benefits cannot favor heat pumps from the economic point of view. This conclusion can also be drawn with learning aspects included, but the economic viability of heat pumps is already better in this latter case. However, even with decreasing installation costs the cost effectiveness of the heat pumps strongly depends on the evolution of energy prices. So, commercializing heat pump systems is one point, but, more importantly, policy makers have to focus on the large difference between gas and electricity prices. Possible measures could be to introduce a separate and cheaper electricity tariff for owners of a heat pump, e.g. only night tariff, or research in thermal energy storage could be stimulated which can lead to using heat pumps when electricity is cheaper. With the current evolution to nearly zero energy buildings (NZEB) the integration of renewable energy sources is a hot topic. PV systems often feed heat pumps, which is an extra incentive for heat pump systems. Mismatch in time between supply and demand asks for thermal energy storage. However this applies mainly to new buildings. For building owners, a gas condensing boiler is still an economically safe investment today.

7. Conclusion

Retrofits of building envelope and heating systems in the residential sector have a very large potential for the reduction of primary energy consumption. From the energetic viewpoint, it is always advised to retrofit the building envelope. The heating system has to be upgraded by choosing a heat production device that delivers the appropriate supply temperature for the emission system, where a heating system with low supply temperature gives better results than a high temperature system. Overall, the air source heat pump has a large energetic saving potential.

In contrast, the economic potential of air water heat pumps strongly depends on the evolution of the energy prices and investment costs. This discrepancy between the energetic and economic results can be diminished by using a more favorable electricity tariff for owners of a heat pump. Nevertheless, today the gas condensing boiler still seems to be a cost effective choice for building owners in Belgium and Germany due to the low gas price with respect to the electricity price. In France, however, especially hybrid heat pumps are a more cost effective investment due to the relatively low average electricity price with respect to the average gas price.

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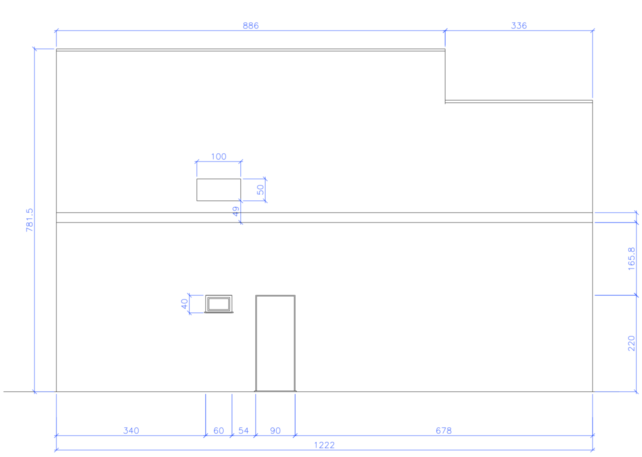
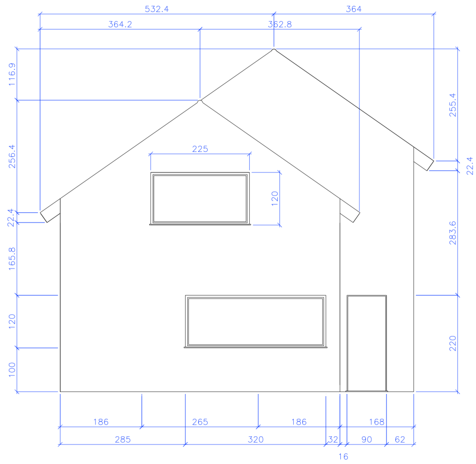
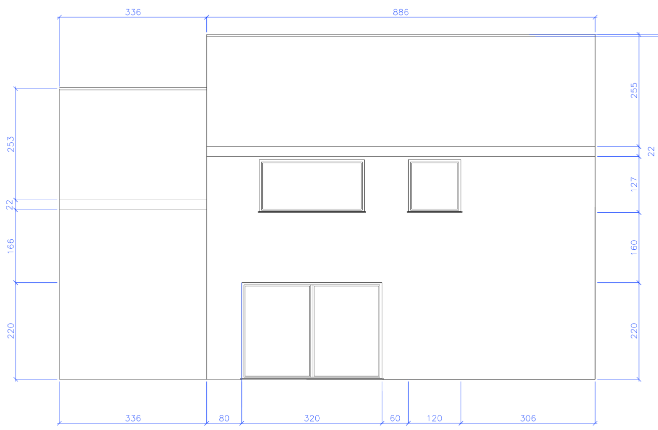
A. Geometry of the building



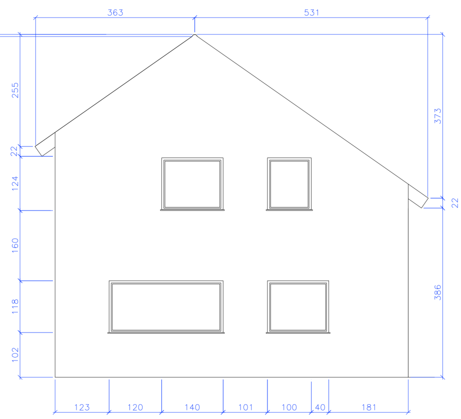
Northern facade



Western facade



Southern facade



Eastern facade

Figure 4: Geometry of the building